MEASUREMENT AND PREDICTION OF THE OFF-ROAD MOBILITY OF SMALL ROBOTIC GROUND VEHICLES

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ABSTRACT

This paper describes a testbed and methods used in performing experiments and collecting quantitative data on the off-road mobility of two small ground robotic vehicles. The data is unique in the sense that it is: 1) unbiased, having been collected and interpreted by personnel independent of the vehicle developers, 2) locomotion-independent, since the same test procedures are followed regardless of whether the vehicle has wheels, legs, or tracks, 3) reasonably general, for the test range features a wide variety of terrain types including rock beds and mud pits, and 4) quantitative, in the sense that the results include measures other than pass and fail, such as voltage, current, and terrain ground truth. The paper reports on efforts to coordinate these testing capabilities with modeling and simulation for the purpose of predicting the mobility performance of a given vehicle on a given terrain. A series of basic to more complex dynamics models of a PackBot are used as a case study, along with their application to analysis of test results and formulating appropriate metrics for performance. Preliminary results in validating the model on steps, ditches, and slopes at the test range are presented.

KEYWORDS: *mobility, mobility metric, mobility prediction, robotic ground vehicle, modeling and simulation*

1 INTRODUCTION

Performance metrics for mobility of small robotic ground vehicles are desirable because they enable benchmarks to be formulated for comparing different systems, and because they enable assessing, selecting, and planning the use of systems for different applications. The interaction between mobile robots and the environment in which they operate is a critical issue that significantly impacts performance and continues to motivate the advancement and application of intelligent system design. The uncertainty and variability of off-road terrains, for example, has challenged ground vehicle designers over many decades. The increasing demand to broaden the scope of a robotic vehicle's capacity to handle structured and unstructured man-made terrains has further motivated a highly integrated understanding of the vehicle and the vehicle-terrain interaction so as to facilitate design of control and planning algorithms that will maximize the probability of successful operations.

Fortunately, mobility of ground vehicles and of robotic ground vehicles in particular, has benefited from the advancement in modeling and computational tools that can be used to evaluate the baseline performance of these systems. However, the ability to quantify the vehicle-terrain interaction remains a major challenge, making it difficult to establish bases for comparison of performance between different systems operating in the same environment. The use of sophisticated intelligent controls on the vehicle and/or including a human-in-the-loop offers certain advantages and robustness, but also introduces challenges for making predictions about performance that can aid operational decision-makers. Figure 1 illustrates the interaction of critical subsystems in a mobile robotic system. In the end, proof of operation of such complex mobile robotic systems requires field testing, tuning, and refinement in the system design tradition.

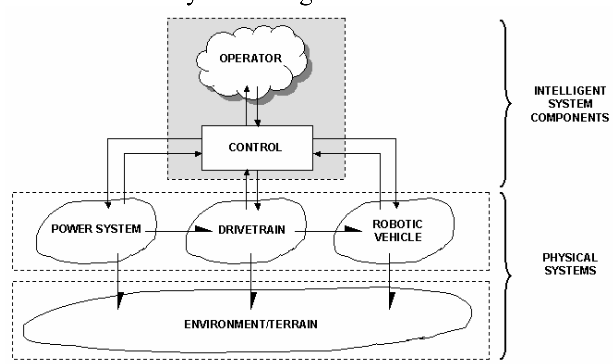


Figure 1. Generic mobile robotic system showing critical components. The interactions occur in various ways. Full arrows indicate signal flow. The half-arrow indicates an energetic interaction conveying flow of power.

Researchers and developers in military and civilian vehicles, planetary rovers, and mobile robotics have all studied the mobility of off-road vehicles. Three widely cited texts by Bekker [3][4][5] summarize work in the first two-thirds of the 20th century, and with Wong [15] form the classical references in the field. These works examine off-road performance of large vehicles such as earth-moving equipment and military transports.

The NATO Reference Mobility Model (NRMM) [1] extends this work. The NRMM, along with the closely related Army Reference Mobility model, is a set of equations and algorithms that predict a vehicle's effective maximum speed based on vehicle physics and terrain properties. This work has also been extended for cold-weather terrains [12]. Although instructive, the models have limited applicability because they are specialized to the soil effects and obstacles encountered by heavy vehicles. A large corpus of research addresses on-road vehicle dynamics. Organizations throughout the world test the safety of vehicles, collecting metrics with the ultimate goal of avoiding crashes. These metrics provide a valuable baseline for our dynamic simulations, but do not go nearly far enough in characterizing off-road performance. A more relevant area of research focuses on planetary rovers. The design and testing phases of the NASA Lunar Rover (LRV) identified basic mobility performance characteristics, such as slope-climbing capability and energy-consumption rate vs. wheel slip [6]. More recently a large body of work has addressed unmanned rovers for the Moon and Mars. A few works have specifically addressed measures of mobility with a weighted set of individual tests [11] [14]. Sukhatme [13] has taken an alternate approach using a statistical, multicriteria evaluation technique for mobile robot performance. His approach is especially relevant because it uses a dynamic computer model validated with a physical robot. An interesting tack was taken by Apostolopoulos [2], who also measured mobility parameters for building dynamic computer simulations. This program synthesizes wheeled rover configurations and predicts their performance. Most of these investigations are restricted to the types of soils and obstacles found on lunar or Martian surfaces. Research by Iagnemma [9] is directly related to our problem. They have developed an off-road simulation model, and validated it with a 1/10-scale physical vehicle driving at high speeds through ditches. We have adopted essentially the same methodology, and are currently applying it to the PackBot and a wider variety of terrain types, all at substantially slower speeds than those of interest to Iagnemma. Research on unmanned ground vehicle mobility [7] also addresses difficult terrain such as vegetation and urban terrain. Recent work reported by Frost, et al [8] describes a robotic test course (Section 2). The current work extends the testing described to date over a wider range of terrain and vehicle types.

2 MOBILITY TESTBED

The small robotic vehicle test range at Southwest Research Institute was developed to provide independent third-party evaluations to support offices of the U.S. Government. A complete suite of tests fall into four categories: an engineering evaluation, endurance tests, mobility over obstacles, and operational scenarios. Other specialized tests, including environmental (vibration, drop, immersion, electromagnetic compatibility), sensors, navigation, and specialized payloads can be conducted upon request. Although our emphasis is primarily on the mobility aspects of the vehicle under test, data is also collected and recorded in other areas, including the operator control unit, command, control, and communications system, obstacle detection and avoidance system, navigation and other sensors, system deployability, reliability, and field-worthiness.

The engineering tests include measuring and documenting characteristics such as weight, physical dimensions, ground clearance, static power requirements, wheel or track friction characteristics, sensor field of view, and communications requirements. Additional evaluations include the robot’s ability to climb ramps of varying inclination and surface characteristics, curbs of varying height, spans of varying width, and the ability of the robot to be teleoperated along a straight line at its maximum controllable speed on asphalt and grass surfaces. During most of these engineering tests, the operator has an unobstructed view of the robot. The on-road operating range of a robot is determined under ideal conditions on a 6100 foot long oval automotive test track. The test starts with the vehicle’s batteries fully charged, and the vehicle is run until the batteries are depleted. Total distance is measured and the average speed is calculated. An efficiency figure of merit is also calculated (meters/watt-hour) using 80% of the rated ampere-hour capacity of the batteries. If the robot system supports real time measurement of voltage and current, this data is used to determine the overall energy usage and efficiency. The off-road range of the robot is similarly obtained, using a 6000 foot course through varied terrain that is predominantly short grass with some modest hills. As in the on road test, total distance is measured and the average speed, and an efficiency figure of merit are calculated.

The third part of the evaluation involves negotiating a wide range of obstacles that are configured to force the robot to encounter, rather than avoid, them. The *railroad track* presents the robot with three paths of varying difficulty. The easiest is a wooden bridge that crosses the rails. The next most difficult is a gravel incline up to the rail. The most difficult route requires the robot to climb the ties and both of the rails. The *irrigation pipe* consists of a variety of metal and PVC pipes that range in diameter from 1 to 8 inches. They are arranged at various angles to the path, and the robot must climb over each of them.

Figure 2. PackBot in large rock bed, Gemini crossing railoroad tracks

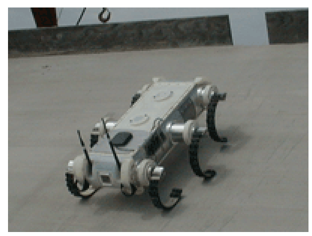
The *culvert* consists of several configurations of concrete drain pipe. A small section two feet in diameter with two back-to-back 45 degree angle segments is used to determine the ability of the robot to enter and maneuver through mild turns. A longer section, with a 90 degree turn tests the capabilities of the robot to execute a right angle turn within the tightly confined space available. Larger, 36" diameter culvert sections are also available. The primary metric for this obstacle is the elapsed time to negotiate the complete obstacle. Success or failure in negotiating the tight turns is also recorded. The *pipe forest* tests the maneuverability of robots in confined spaces. It consists of an array of closely spaced upright PVC pipes. A narrow serpentine path is defined for the robot through the array by removing some of the pipes. The metrics for this test include number of traps and reversals during the traversal, as well as total elapsed time.

The *rock obstacle* consists of four rock beds, each containing rocks of a particular size and shape. One bed has large rock slabs arranged at various angles. The other three beds consist of relatively homogeneous rocks (roughly 2, 4, or 8 inches in height) arranged in a random pattern. The pattern is sufficiently dense that a robot must drive over most of the rocks. The beds are connected by short grass paths. Individual transit times are recorded through each rock bed, as well as traps, reversals, high centers, and equipment failures such as losing a track or overturning.

The *cultivated field* consists of a series of parallel furrows to simulate plowed ground. The *vegetative obstacles* consist of several 30 meter lanes that traverse local vegetation of varying height, compliance, and density. This is one of the few obstacles on the course that change from test to test due to weather conditions and time of year. This variability is taken into account when comparing scores between runs made at different times and under different climatic conditions. The metrics include elapsed time and energy usage (if the robot is suitably equipped to measure power). Additionally, the propensity to ingest grass and other vegetation into the tracks, wheels, or legs is observed and documented.

The *sand pits and dunes* consist of several sand beds. One bed consists of loose dry sand. A second bed has small parallel furrows, and the third bed has two large parallel dunes with 30 degree (approximately) slopes. This obstacle is used to determine the robot's mobility in loose, gritty materials, as well as to document the "footprint" or signature it leaves in the loose sand. The primary metric is the transit time through each of the beds.

The *mud pit* consists of thick mud that the vehicle must cross several times, once without stopping, and once by stopping, spinning in place, and then starting again. This obstacle demonstrates the ability of the mobility system to perform under muddy conditions. Elapsed transit time and energy usage are the significant metrics. The *water obstacles* consist of a one-acre, lined pond, and a short flowing "stream." The pond is five feet in depth, and is used to test robots that are submersible, or that can swim. The moving water obstacle replicates a short section of stream or river. Water flowing at various velocities is controlled through a system of water tanks, pumps, and sluice gates. The stream obstacle has packed earth banks and a concrete bottom that can be covered with gravel, mud, or other materials. During testing, the robot first maneuvers in shallow standing water. This is followed by tests in a moving current, where the robot moves both parallel and perpendicular to the water flow. Metrics include transit time from bank to bank across the moving water, energy usage under various flow conditions, stability and performance under conditions of longitudinal and transverse flow. The integrity of the hull and ability to climb the banks when the tracks/wheels/legs are wet are also observed and recorded.



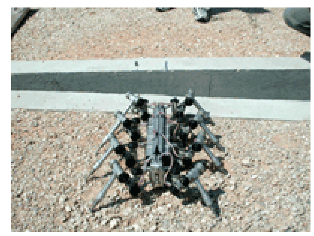


Figure 3. RHex-R on ramp, Scorpion crossing trench

The *variable-width trench* obstacle tests the ability of the robot to cross (the robot must span or jump the gap) a deep trench. The obstacle consists of a variable width, four-foot deep concrete trench. The width varies linearly from four inches at the narrow end, to four feet at the wide end. The robot is caused to cross the trench at increasing wider gaps until it falls in, and is tested under static (no head start) and running conditions. This obstacle can also be used to determine the minimum width "tunnel" that a robot can traverse without getting trapped.

Operational scenarios are designed to test the cross-country mobility of the robot under representative field conditions. The tests can be structured in many ways, depending upon the capabilities, limitations, and intended mission of the vehicle and payload. These are "system" level tests, that involve the platform, operator control unit, communications system, navigation system, obstacle detection and avoidance system (if supported), and any specialized payloads (e.g., reconnaissance, sampling, target designation). A typical test involves unrehearsed movement to several "goal points" or objectives while traversing a variety of terrains. A typical scenario involves cross-country movement through four or more lanes, each several hundred meters in length, and consisting of a variety of vegetation, natural, and man-made obstacles. The operator is located in a remote position where they cannot directly observe the robot or its environment, and controls the robot and payload using teleop and other sensor information. Each of the legs terminates at a "goal point" where the operator is required to conduct reconnaissance, surveillance, or some other task prior to continuing on the mission. Metrics include elapsed time for each leg, deviation from the straight-line distance between the end points, energy consumption, the level of task achievement, endpoint navigational accuracy, and for semi-autonomous systems, bi-directional communications volume between the operator and the robot.

3 PACKBOT MOBILITY

The iRobot "PackBot" is arguably the current "standard" for small, robust, teleoperated robotic vehicles. The PackBot was developed under the DARPA Tactical Mobile Robotics program. During its short service life, it has seen operational use at the World Trade Center, and in tactical military operations in both Afghanistan and Iraq. The mobility of the PackBot derives from the combination of "standard" tracks, front-mounted articulator arms, and a dual-motor drive system. The articulators can be used as primitive "feet" to lever the PackBot over obstacles and terrains to support the tracks, or to flip the entire platform over when it becomes inverted.

Several versions of the PackBot have been tested on the Small Robotic Vehicle Test Bed at SwRI, beginning with early TMR testing in 1998, continuing up through tests involving integrated sensor payloads and mobility testing in 2003. SwRI is the custodian of a Government-owned, late model PackBot, and uses it for a variety of test purposes, payload development, and obstacle design and characterization. As the PackBot has evolved, its capabilities and field-hardiness has increased significantly with only a modest growth in size and weight.

4 RHEX MOBILITY

The RHex series of robots are six-legged "hexapods." These robots were developed under the DARPA Controlled Biological and Biomimetic Systems (CBBS) program by the University of Michigan and McGill University. RHex was developed, in part, to answer the question "why do legs matter?" These robots have been tested at SwRI several times, and have been getting increasingly more capable and test-worthy. During movement, the six resilient legs swing in a circular motion, maintaining a tripod gait, with two legs on one side and one on the other in contact with the ground. There are several versions of the RHex platform. RHex (1.0) is a lightweight (18 pounds) research version and is used to develop and test various control algorithms, gaits, and sensors. RHex-R (shown earler) is a ruggedized version of the RHex robot. The operational version was developed to address an intelligence community operational test scenario, and it is somewhat heavier and larger than the research platforms. This most recent design incorporates two driving cameras, GPS, and a digital compass, as well as a waterproof chassis. The robot uses standard military batteries (BB-390 or BB-2590) to power the robot and the OCU, and it incorporates commercial data and video systems to support teleoperation.

Table 1 compares the relative performance of the current PackBot and RHex platforms, based on limited testing. The PackBot is generally faster, can climb steeper slopes and higher curbs, and travels more meters per watt-hour of energy. RHex appears to have better mobility and higher speed in certain types of rough terrain, as shown by the rock bed data, and to have similar power efficiencies for on- and off-road terrains.. We note that the PackBot has over four years of focused development and testing under its tracks, while the RHex-R vehicle has just begun the hardening and optimization cycle.

Table 1. PackBot and RHex Comparison

Event	PackBot 4a	Rhex-R
Weight, lbf	45	36
Curb climb, in	10.5	8.75
Ramp up, deg	37	32
Speed $^{(1)}$, m/sec	2.7	1.0
Rocks $^{(2)}$, m/sec	.14	.25
η on-road, m/Wh	59	27
η off-road, m/Wh	40 $^{(3)}$	22

(1) level asphalt; (2) Rock Channel and Large rock bed combined times; (3) data from February 2003 test on Gen. 4.

The SwRI testbed provides a critical service in evaluation of mobile robotic systems. The value of physical testing remains very high, in part because of the insights gained by developers in the process of serial testing. However, as complexity and intelligence grow to satisfy design and mission requirements, it is becoming increasingly necessary to develop systematic methods to identify and quantify the factors that significantly impact the performance of these systems. It is anticipated that these methods will involve the integration of state-of-the-art testing with modeling and simulation capability.

5 MOBILITY PERFORMANCE PREDICTION

Physical testing is practically limited by the number of obstacle courses available and the resources required for testing. Further, it is not clear how to extrapolate results for a given course to predict mobility on terrain that is markedly different. Continuing advances in testing and in modeling and simulation are making it possible to begin formulating an integrated approach, wherein lessons learned from a testbed can be extended by simulation. Likewise, model-based studies of mobile robots traveling over specified terrains can support the design of tests either to answer specific questions, or to improve the modeling and simulation processes.

Figure 4 illustrates a long-range vision: an environment that predicts the interaction between a mobile robot and complex terrain. Prediction software may use a computer-aided design (CAD) model of an existing (or proposed) robot and a terrain model to simulate the robot-terrain interaction. Robot performance will then be measured in a variety of ways, including traversal speed, payload, sensor stability, and the ability to traverse obstacles. From these measurements, the system can then predict the probability that a robot can traverse a given terrain.

Such a system will derive a number of benefits by using simulation technology: a large number of simulations can be run over terrain for which no physical model exists; experiments can be performed to determine the specific conditions where mobility succeeds and fails; and statistical measures can be used to characterize mobility more completely. Further, this technique can help developers tighten the loop in future robot design cycles, and to evaluate a particular robot configuration that is optimal for a given mission. Modeling and simulation technologies have limitations. It is necessary to demonstrate that models can be sufficiently detailed to be operationally relevant, yet can provide solutions in a timely manner. Also, it is critical to validate the simulation results using physical measurements and test runs. A well-conceived validation plan will help the physical testing and simulation to improve each other until the simulation results are robust enough to allow prediction.

To demonstrate the challenges foreseen, a limited set of experiments were conducted with the PackBot at the SwRI testbed. The PackBot is of interest because of its commercial availability, its engineering maturity relative to other systems, and its growing popularity among tactical users. A first step toward supporting the long-term vision is to model the PackBot and predict its performance in three idealized obstacle geometries: steps, ditches, slopes. These represent simple yet practical geometries that can be easily parameterized and are thus attractive for baseline study. The scope of this initial study is also limited to non-responsive terrains, and in particular the results on relatively hard (e.g., cement) surfaces are reported. Additional testing and modeling with terrain-response is the subject of ongoing studies.

The principal goal is to investigate ways for developing, verifying, and validating mobility models for these obstacle geometries. Three basic steps are followed: (1) The PackBot is systematically exercised in the testbed, and measurements made of the maximum step height, ditch width, and slope grade that can be successfully negotiated. (2) Model studies are conducted to characterize the obstacle clearing performance, and simulation models developed to determine the performance of a model robot on a simulated obstacle. (3) The real and simulated performance are compared and evaluated, with an emphasis on understanding the influence of model/simulation parameters on the agreement with the empirically observed results.

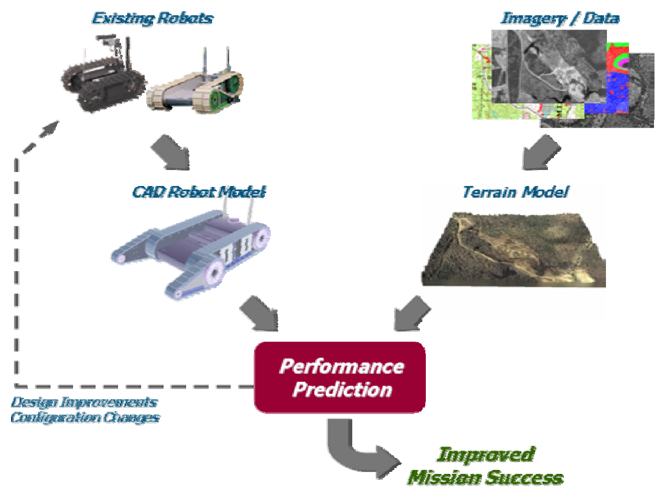


Figure 4. Long-Range Vision for Predicting Mobility

Test Results. A PackBot (unit 170) was tested with no flippers, no head/neck, two batteries, and cleated tracks. Table 2 summarizes the obstacle clearing performance of the PackBot. For example, the PackBot cleared a single step obstacle while moving a its lowest speed. A test on a sandy slope is also included in this table.

Table 2. PackBot Obstacle Clearance

Speed	Step (in)	Ditch (in)	Slope Concrete (deg)	Slope Sand (deg)
Slowest creep	5.0	11.0	35.1	
Fastest creep		11.5		29.9
Slow			38.0	
Medium		18.0	38.0	

The limit on the slope climb in concrete gives a rough indication of the effective track belt friction coefficient, μ (the PackBot uses a solid santoprene belt with cleats). This might indicate a μ of about tan(38)=0.78. Several pull tests using a force scale showed that the effective μ might range from 0.66 on the low side to about 0.8. These estimates are essential for any model study, and sufficient for the case of hard surface mobility prediction studies and metric formulation. In addition, the PackBot data logging capability was used to provide measurements that could be used to interpret the results from the tests and/or for comparison with modeling and simulation studies.

Modeling Studies. The modeling and simulation studies conducted to date include a combination of analytical and computational models. Analytical models that only represent the most significant effects in a problem can be very effective in providing insight into a problem, and subsequently in forming useful measures of performance. This was recognized early by Bekker [5] and others who have employed empirical relations and data as needed. The limited space here precludes detailed derivation, but a summary of the models developed for this study and their application is given in the following discussion. These models are also useful, if not essential, for interpreting results from more complex, computational (simulation) models and for designing future testing.

Computational models were formulated using the commercial multibody dynamics software, MSC.ADAMS, as well as COSMOS/Motion (C/M). The computational engine of C/M is ADAMS, however C/M is directly integrated with the solid modeling package, SolidWorks. Models in C/M can be exported for further (and more extensive) analysis in ADAMS. The use of these software packages formed an initial evaluation of a CAD-driven modeling process. The process involves developing or utilizing assembly drawings in SolidWorks, analysis/simulation in C/M, and export if necessary into ADAMS. To facilitate the process, the PackBot manufacturer, iRobot Corporation, provided a complete SolidWorks model for use in this study. In the end, however, this model was primarily used to study the robot construction and to determine geometric and mass properties.

Step Clearance. Physical testing showed that the PackBot can clear a step of h = 5 inches (see Figure 5 for parameter descriptions; the PackBot wheel radius is 3.5 inches). In the experiments, it was observed that clearance was aided when a track cleat was able to 'catch' the lip of the step, pulling the robot over. A simple (quasistatic) model reveals that to hold the weight, W, on a vertical step allowing a driven climb, it is necessary to have a friction coefficient (at A and B) of,

$$\mu \geq \frac{L_2}{L_1 + r/a}, \quad \text{a}=\sqrt{1-\left((h-r)/L\right)^2}\,. \qquad (1)$$

For L_1=7 in, L_2 = 13 in (L=L_1+L_2), r = 3.5 in, and h = 5.0, climbing requires $\mu \geq 1.24$. Thus, the climb was not solely friction-enabled, but required the cleat 'action'.

A model of the PackBot developed in SolidWorks and exported into ADAMS is shown in Figure 6. This model employs a 'pseudotrack' concept (developed at SANDIA National Laboratories by Paul Klarer) to model the track. The simulation in ADAMS using a μ of about 1.25 showed that the PackBot could clear the obstacle under these conditions.

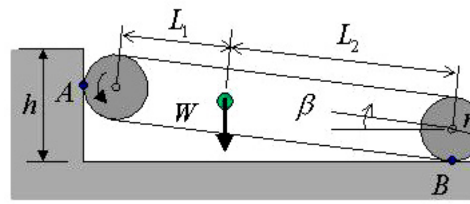


Figure 5. Basic geometry of a tracked robotic vehicle in a step climb.

Note, once a tracked vehicle such as the PackBot overcomes the step, a complete obstacle clearance requires that the center of gravity be passed in a stable fashion. This second stage of the clearance can be determined by an analytical model, similar to that found by Janosi [10]. For the PackBot geometry, this indicates that the maximum step is about 8.07 inches, but the PackBot exceeds this with a value of about 9.125 inches, probably because of the influence of cleats, with the possible influence of travel speed.

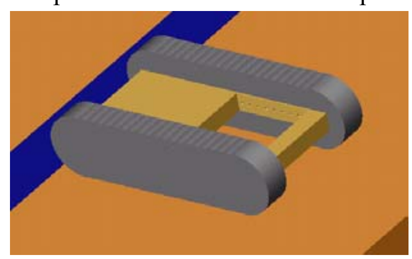


Figure 6. The PackBot was modeled in a reduced form using SolidWorks. The model is shown here positioning to climb a step obstacle.

Ditch Clearance. The ditch clearance problem has been modeled using an analytical two-dimensional Lagrangian model (not presented here) and by a 3D model built in SolidWorks and simulated in C/M. The C/M simulation comes fairly close to predicting results from testing. For example, in the graph of Figure 7, the green and red lines represent successful and failed attempts, respectively. For a ditch width of 18 inches, a PackBot with an initial velocity of 1.8 m/sec and greater has a high probability of clearing the ditch. This result is predicted by a C/M simulation. In the series of 'snapshots' shown in Figure 8, the final state would require the PackBot drive to 'pull' the vehicle body over the lip, relying on the aid of the cleats on the track. This was observed in tests. The ability for the PackBot to position itself at the take-off point with the minimal initial velocity should be included as a requirement for a successful ditch clearance.

Influence of Auxiliary Systems: Motor Drive. For both the step and ditch geometries, reasonable metrics for quantifying the PackBot's ability to traverse the obstacle can be formulated using basic mechanics models and simulations. It is implied, however, that a successful step climb requires certain geometric and material property (i.e., friction) characteristics in addition to adequate torque in the drive system to turn the wheels. In some of the ditch crossings, the PackBot narrowly cleared the distance, becoming stuck. Sufficient torque capability remained, however, so the drive system was able to 'grind' out a successful clearance. It is evident that the role played by the drive system can be significant. For this reason, the PackBot motor drive and drivetrain systems were studied, and a baseline model developed. This model includes a simple battery model driving a dc bus that powers two simplified PWM motor controllers (left and right) driven by throttle and steer control signals. The preliminary model can be extended to include other effects, but as it stands it allows us to study the effect of the power capacity of the drive system on the obstacle clearing maneuvers.

Figure 7. Physical testing of the PackBot in a ditch crossing. The pass/fail metric is parameterized here using speed at the 'take-off' point and ditch width.

Slope Clearance. Modeling how the PackBot climbs a slope can employ a standard model for longitudinal performance,

$$m\dot{V} = \sum F$$
$$= \underbrace{\mu W \cos\theta}_{\text{drive force}} - \underbrace{W \sin\theta}_{\text{load due to grade}} - \underbrace{F_r}_{\text{rolling resistance}}, \quad (2)$$

where a simple traction force is assumed to work against the grade and rolling resistance forces (all other effects negligible). From this equation, a simple estimate can be derived for velocity climbing the grade, assuming a known initial velocity state at the base, giving,

$$V = V_o + \underbrace{g(\mu\cos\theta - \sin\theta - f_r)}_{=A=\text{ constant acceleration/deceleration}} \cdot t, \quad V > 0. \quad (3)$$

In this relation, f_r is a rolling resistance coefficient. This simple model provides a measure of the influence of the initial velocity (the 'running start') and of the friction coefficient, μ.. Decisions can be made based on this simple relation related to whether a slope can be negotiated.

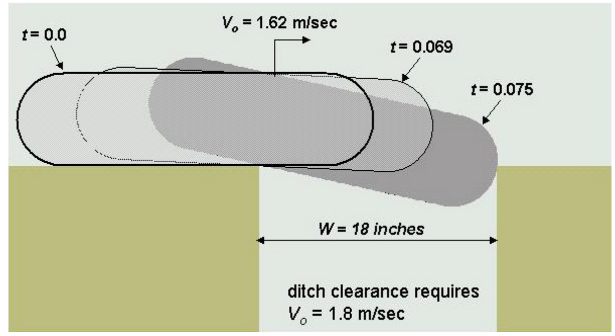


Figure 8. Simulation of a failed ditch crossing using COSMOS/Motion. The PackBot body outline is shown at the initial take-off point and at two successive points thereafter.

The simple model given above assumes the drive is able to deliver the necessary torque. This model can be augmented to include the power-limiting characteristics of the drive, however the modeling effort in this study explored the integration of the drive system model within an ADAMS environment. Several test cases were conducted showing very good correspondence with the observed studies. For example, while the PackBot is able to climb a 38 degree slope under normal friction conditions (see test result table), with μ nominally 0.78, the graphs in Figures 9 and 10 show how a failed slope clearance is predicted for a slightly lower friction with $\mu = 0.7$. Integration of the motor/drive system enables tracking currents, for example, which here show good correspondence with data logged during the testing (peaks in the range of 6 to 7 A).

6 DISCUSSION

This paper reports on an ongoing effort to integrate physical testing with modeling and simulation, with the intent of enhancing the evaluation capability of the robotic vehicle testbed, and to aid the development of a model-based mobility prediction and mission planning simulation environment. These are essential elements in establishing quantitative measures for performance of complex vehicle systems operating in highly uncertain environments. One data point was included for the PackBot traversing a sloped sand pit. This test is an indicator of the need to progress in these efforts to incorporate responsive terrain models, as well as other complex terrain geometries. The well-known difficulty surrounding this area offers considerable challenges.

Results from testing demonstrate that the testbed is capable of discriminating between various platforms. For example, the testing described in Sections 3 and 4 indicates to date that RHex shows the potential to provide a large percentage of the mobility of the PackBot, at significantly reduced size and weight.

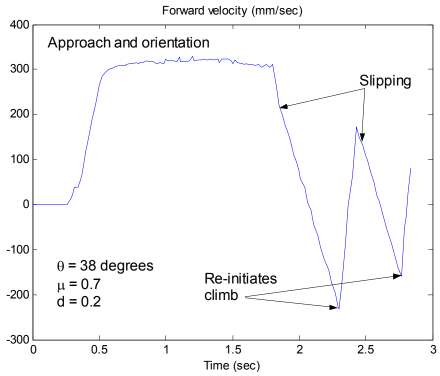


Figure 9. The forward velocity of a PackBot body as it tries to climb a 38 degree slope. In this case, the coefficient of friction is on the 'lower' side. Note that the obstacle is not cleared in this simulation (results from using a 3D simulation in MSC.ADAMS).

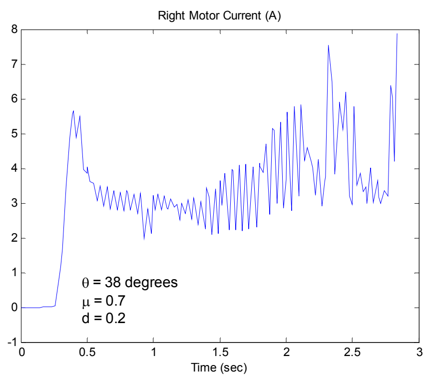


Figure10. The current in the right motor corresponding to the failed slope climbing maneuver shown in Figure 9.

Evaluation in the testbed will support modeling and simulation efforts. This is challenged, however, by the inherent difficulty in predicting the performance of running gear (wheels, tracks, legs, etc.) interacting with various terrain of interest. Using available commercial computational dynamics modeling environments is helpful, but the simulations can be time consuming. Further, both robotic platforms tested were teleoperated, implying that a modeling and simulation environment should eventually allow for human-in-the-loop simulation. This is currently not possible with the methods used, and future study will require examination of techniques that can provide such a capability.

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